MNRAS, accepted

Thickening of galactic disks through clustered star formation

Pavel Kroupa

Institut für Theoretische Physik und Astrophysik
Universität Kiel, D-24098 Kiel, Germany

Summary

The building blocks of galaxies are star clusters. These form with low-star formation efficiencies and, consequently, loose a large part of their stars that expand outwards once the residual gas is expelled by the action of the massive stars. Massive star clusters may thus add kinematically hot components to galactic field populations. This kinematical imprint on the stellar distribution function is estimated here by calculating the velocity distribution function for ensembles of star-clusters distributed as power-law or log-normal initial cluster mass functions (ICMFs). The resulting stellar velocity distribution function is non-Gaussian and may be interpreted as being composed of multiple kinematical sub-populations.

The velocity-dispersion of solar-neighbourhood stars increases more rapidly with stellar age than theoretical calculations of orbital diffusion predict. Interpreting this difference to arise from star formation characterised by larger cluster masses, rather than as yet unknown stellar-dynamical heating mechanisms, suggests that the star formation rate in the MW disk has been quietening down, or at least shifting towards less-massive star-forming units. Thin-disk stars with ages 3–7 Gyr may have formed from an ICMF extending to very rich Galactic clusters. Stars appear to be forming preferentially in modest embedded clusters during the past 3 Gyr.

Applying this approach to the ancient thick disk of the Milky Way, it follows that its large velocity dispersion may have been produced through a high star formation rate and thus an ICMF extending to massive embedded clusters ($\approx 10^{5-6}\,M_\odot$), even under the extreme assumption that early star formation occurred in a thin gas-rich disk. This enhanced star-formation episode in an early thin Galactic disk could have been triggered by passing satellite galaxies, but direct satellite infall into the disk may not be required for disk heating.

Subject headings: Galaxy: formation – Galaxy: evolution – Galaxy: structure – globular clusters: general – open clusters and associations: general – stars: kinematics

1. INTRODUCTION

Observations have shown that the Milky Way (MW) and other comparable disk galaxies are composed of a number of more-or-less discrete components. The broadest categories of these comprise the central bulge with a mass $\approx 10^{10}\,M_\odot$ and characteristic radius of about 1 kpc, the Galactic spheroid (or stellar halo) with a mass $\approx 10^8\,M_\odot$ being mostly confined to within the solar radius and also containing globular clusters that add up to a mass of about $10^{6-7}\,M_\odot$, the embedded stellar and gaseous disk, and a hypothesised extensive dark matter halo surrounding the lot and extending to 20–200 kpc (Gilmore, Wyse & Kuijken 1989; Binney

& Merrifield 1998, hereinafter BM, for reviews). For the MW, the disk can be subdivided into at least two components, namely the thin disk with a mass of about $M_{\rm disk} = 5 \times 10^{10}\,M_\odot$ with exponential radial and vertical scale-lengths of approximately $h_R = 3.5$ kpc and $h_z = 250$ pc, respectively, and the thick disk with roughly $h_{{\rm thd},R} = 3.5$ kpc and $h_{{\rm thd},z} \approx 1000$ pc. Near the Sun, the thick disk comprises about 6 per cent of the thin disk mass (Robin et al. 1996; Buser, Rong & Karaali 1999; Vallenari, Bertelli & Schmidtobreick 2000; Chiba & Beers 2000; Kerber, Javiel & Santiago 2001; Reylé & Robin 2001), so that the thick disk mass amounts to $M_{\rm thd} \approx (0.2-0.3) \times M_{\rm disk}$. Mass-models of the MW, let alone of other disk galaxies, remain rather uncertain though (Dehnen & Binney 1998).

The structure of galaxies is linked to the physics of their formation which is the topic of much on-going research (e.g. Chiba & Beers 2000; Reylé & Robin 2001). Relevant to the long-term survival of thin disks is understanding the origin of the Galactic thick disk. This component is made up mostly of low-metallicity ($[{\rm Fe/H}] \lesssim -0.4$) stars that have a velocity dispersion perpendicular to the disk plane of $\sigma_{z,{\rm obs}} \approx 40$ pc/Myr, compared to the significantly smaller σ_z of the thin disk, which varies from about 2–5 pc/Myr for the youngest stars to about 25 pc/Myr for stars about 10 Gyr old (Fuchs et al. 2001). The classical work of Wielen (1977) has shown that this increase can be understood as a result of progressive heating of the thin disk population through a diffusive mechanism.

The heating agent remains elusive though. This is nicely evident in the work of Asiain et al. (1999), who find that spiral arms and a central Galactic bar alone cannot account for the diffusion, and as shown by Fuchs et al. (2001), scattering off molecular clouds also cannot produce the necessary heating. Jenkins (1992) also shows that heating through spirals and molecular clouds and adiabatic heating through mass growth of the Galactic disk do not lead to the observed rise in velocity dispersion with stellar age. Even worse, assuming orbital diffusion does operate from some yet to be discovered scattering agent(s), the large σ_z for thick-disk stars cannot be obtained from an extension of the Wielen-heating law. It follows that the thick disk must have formed under different conditions. This may be expected naturally, given that thick disk stars are not substantially younger than the old halo stars, thus having been born at the very beginning of the formation of the Galactic disk (e.g. Gilmore & Wyse 2001).

There are two broad classes of theories for the formation of a thick disk component. One class of models involves the settling of an initially hot proto-galactic gas cloud. A thick disk may form as a result of dissipational settling to a thin disk (Burkert, Truran & Hensler 1992). According to the alternative hypothesis the MW formed from many smaller components in a chaotic manner, leading first to the formation of the spheroidal components, and a few Gyr later, of the thin gaseous disk. Perturbation of the early thin stellar disk through continued accretion of dwarf galaxies may have lead to a thick disk component, a scenario that has the advantage of not producing a vertical metallicity gradient in the disk. N-body computations, however, may cast doubt on this scenario, because realistic dwarf galaxies that have densities comparable to the parent galaxy are likely to be destroyed before they venture close enough to the disk to cause significant vertical heating (Huang & Carlberg 1997; Sellwood, Nelson & Tremaine 1998; Velazquez & White 1999), but the situation is not clear since adequate computational resolution of gas-rich and star-forming galactic disks is at present not possible. The current state of understanding concerning the MW thick disk is reviewed by Norris (1999), who stresses that its origin remains unclear, and by Gilmore & Wyse (2001), who present the first results of an extensive observational UK–Australian collaboration towards casting light on this issue.

This paper addresses an additional mechanism that may be relevant to the thickness of disks, and which is motivated by recent progress on understanding star-cluster formation. Section 2 summarises clustered star formation and details the calculation of the stellar velocity distribution function. It also discusses

known heating mechanisms active in disk galaxies that increase the velocity dispersion of stars with time. The large velocity dispersion of the thick disk is considered in Section 3 by studying the velocity-field produced in a thin disk in which star-formation is actively on-ongoing. The initial cluster mass function (ICMF) required to give the observed velocity dispersion is constrained. Similarly, the residuals of thin-disk age–velocity-dispersion data over current understand of secular disk heating are analysed and linked to the star-formation history in Section 4. Section 5 contains a discussion of the findings, and concluding remarks follow in Section 6.

2. KINEMATICAL IMPLICATIONS OF CLUSTERED STAR FORMATION

Stars are essentially never observed to form in isolation, but rather in a spectrum of diversely-rich clusters. As outlined in Kroupa (2001a) and Boily & Kroupa (2001), a star-cluster forms stars over a time period $\tau_{\rm clf} \approx 1 - 2$ Myr in a contracting gas-cloud. Because the collapse time of an individual proto-star takes of the order of 0.1 Myr $\ll \tau_{\rm clf}$, each proto-star decouples dynamically from the gas and has enough time to add to the growing star+gas system that is, consequently, approximately in virial equilibrium at any time provided the proto-cluster crossing time (eqn 1 in Kroupa 2001a) is shorter than $\tau_{\rm clf}$. This is true for cluster masses $M_{\rm cl} \gtrsim 500\, M_\odot$ and cluster radii of 1 pc. In sufficiently rich clusters, O stars terminate star-formation, and a large proportion of the cluster stars become unbound as a result of rapid expulsion of the remaining gas and the intrinsically low star-formation efficiency, $\epsilon = M_{\rm cl}/(M_{\rm cl} + M_{\rm gas}) \lesssim 0.4$, where $M_{\rm cl}$ and $M_{\rm gas}$ is the mass in stars and gas, respectively, before gas-expulsion. Observations of very young clusters support this scenario. For example, the Orion Nebula Cluster is at most 2 Myr and probably only a few 10^5 yr old, and already largely void of gas. Similarly, the massive 30 Doradus cluster in the Large Magellanic Cloud is not much older and has already removed its gas.

Direct computations of these processes using the Aarseth state-of-the art direct N-body code are now available. Beginning with $N = 10^4$ stars in an Orion-Nebula-Cluster-like configuration, and assuming $\epsilon = 0.33$ with the residual gas being blown out faster than the cluster's dynamical time, Kroupa, Aarseth & Hurley (2001) find that about 2/3 of the cluster stars are lost and form a rapidly expanding stellar association, while a Pleiades-like cluster condenses as a nucleus near the origin of the flow. The relative number of massive stars remaining in the core that forms the cluster, and those that are lost, depends on the initial concentration of the cluster prior to gas expulsion, and whether the massive stars form near the centre of the cluster. This scenario is supported by the fact that the velocity dispersion in the Orion Nebula Cluster is super-virial (e.g. Jones & Walker 1988), so that it is probably expanding now (Kroupa, Petr & McCaughrean 1999; Kroupa 2000; Kroupa, Aarseth & Hurley 2001). Especially striking in this context is the very recent measurement of the velocity dispersion of stars in the 30 Doradus cluster by Bosch et al. (2001), who find $\sigma \approx 35$ pc/Myr. This is too large for the cluster's mass, and the authors attribute the surplus kinetic energy as being due to binary-star orbital motion and a binary proportion among the massive stars of 100 per cent. The notion raised here is that the velocity dispersion may also appear inflated due to recent gas blow-out. This notion that star clusters form as the nuclei of expanding OB associations is also (retrospectively) supported by the distribution of young stars around the 30 Doradus cluster suggesting it is the core of a stellar association (Seleznev 1997), and the likely association of the α Persei cluster with the Cas–Tau OB association noted by Brown (2001), and other moving groups with star-clusters (Chereul, Crézé & Bienaymé 1998; Asiain et al. 1999). Furthermore, Williams & Hodge (2001) note that most of the young clusters in M31 are located within large OB associations.

The unbound population expands approximately with a one-dimensional velocity dispersion, σ, typical

of the pre-gas-expulsion cluster+gas mixture. Neglecting factors of the order of one,

$$\sigma \approx \sigma_{0,\mathrm{cl}} = \sqrt{\frac{G\,M_{\mathrm{cl}}}{\epsilon R_0}}, \tag{1}$$

where $G = 0.0045\,\mathrm{pc}^3/(M_\odot\,\mathrm{Myr}^2)$ is the gravitational constant and R_0 the characteristic embedded-cluster radius. It becomes immediately apparent that $\sigma_{0,\mathrm{cl}} = 40$ pc/Myr (1 km/s$\approx$1 pc/Myr) corresponds to

$$\frac{M_{\mathrm{cl}}}{\epsilon R_0} = 10^{5.5}\,M_\odot/\mathrm{pc}, \tag{2}$$

coming close to a typical globular cluster mass if $\epsilon\,R_0 = 0.3$ pc, which is typical for young embedded clusters that have characteristic radii $R_0 \approx 1$ pc ($R_0 = 1$ pc is assumed in what follows, unless stated otherwise; examples of results with $R_0 = 5$ pc are given in Fig. 8). Most of the variation of σ stems from variations of the embedded cluster mass which spans many orders of magnitude in contrast to the typical radii of modest embedded clusters and very young massive clusters, all of which are more concentrated than a few pc. For example, local modest embedded clusters have $R_0 \lesssim 1$ pc (Kaas & Bontemps 2001; Lada & Lada 1991), while the rich Orion Nebula Cluster has $R \approx 2$ pc (Hillenbrand & Hartmann 1998). Young massive clusters in external galaxies have $R \approx 2-5$ pc (e.g. R136 in the Large Magellanic Cloud: Massey & Hunter 1998; Sirianni et al. 2000) and in massively interacting gas-rich galaxies, the Antennae, the young massive clusters remain unresolved with $R \lesssim 5$ pc (Whitmore 2001). These clusters are, however, already void of their gas despite being less than a few Myr old, so they should have already expanded ($R > R_0$). This is also true for the somewhat older clusters in a sample of early-type galaxies compiled by Larsen et al. (2001) ($R \lesssim 4$ pc), and in M31 Williams & Hodge (2001) note cluster radii $R \lesssim 5$ pc for cluster ages between about 10 and 200 Myr.

Expansion also implies that the observed velocity dispersion in clusters is smaller than $\sigma_{0,\mathrm{cl}}$. For example, Ho & Filippenko (1996) measure a line-of-sight velocity dispersion of about 11–16 pc/Myr for two extragalactic young massive star clusters. These have inferred masses of about $10^4\,M_\odot$ and are 10–20 Myr old. Smith & Gallagher (2001) find 13 pc/Myr for a young massive cluster (60 ± 20 Myr old) in M82, and deduce its mass to be about $10^6\,M_\odot$. If the present notion is correct and if $\epsilon = 0.3$, then the deduced cluster masses correspond to only about 30 per cent of their birth stellar masses (M_{cl}).

Star-clusters with masses indicated in (2) are observed to form in profusion whenever gas-rich galaxies interact or are perturbed (Lancon & Boily 2000; Larsen 2001 for overviews). It is thus feasible that eqn 2 may indicate that the thick disk resulted from massive clusters forming in a thin disk, rather than being produced through orbital scattering by a merging satellite galaxy. Perturbation of an early thin and gas-rich MW disk by a passing satellite may suffice to trigger the required star formation.

2.1. The velocity distribution function

To address the above question, the distribution function of stellar velocities resulting from a burst of star formation needs to be estimated. Attention is focused on velocities perpendicular to the Galactic disk because motions in the plane are much more difficult to handle analytically since they depend on the evolving mass distribution throughout the entire MW. An extension to include the velocity ellipsoid would go beyond the scope of this scouting work, but will be addressed in future contributions.

As an ansatz the distribution of stellar velocities in one-dimension (perpendicular to the Galactic disk, v_z) in the cluster prior to gas-expulsion is assumed to be Gaussian (i.e. a one-dimensional Schwartzschild

distribution),

$$\mathcal{G}(\sigma_z, \overline{v_z}) = \frac{1}{\sqrt{2\,\pi}\;\sigma_z} e^{-\frac{1}{2}(\frac{v_z - \overline{v_z}}{\sigma_z})^2}, \tag{3}$$

$\overline{v_z}$ being the centre-of-mass velocity of the cluster, and $\int_{-\infty}^{+\infty} \mathcal{G}\, dv_z = 1$. Gas expulsion leads to isotropic expansion, and the velocity dispersions in galactic radial and tangential directions can be linked to the z-component via the epicyclic approximation if sufficiently small compared to the circular velocity about the galaxy (Binney & Tremaine 1987, hereinafter BT). Large expansion velocities would require detailed orbit integration in a self-consistent potential, which goes beyond the aim of the present study. After the gas is expelled from the cluster the major part of the stellar population is assumed to expand freely conserving this distribution but with a velocity dispersion somewhat reduced due to self-gravity, leaving behind the nucleus that forms the bound cluster (Kroupa et al. 2001). The cluster fills its tidal radius and has a much smaller velocity dispersion than $\sigma_{0,\rm cl}$, but analytical quantification is difficult since the processes operating in shaping the cluster are complex (three-body and four-body encounters re-distributing kinetic energy into potential energy, stellar evolution, tidal field).

The stellar velocity distribution function after gas expulsion for an ensemble of co-eval identical clusters with mass $M_{\rm cl}$ becomes

$$\mathcal{V}(v_z, M_{\rm cl}) = \kappa\, \mathcal{E}(v_z, M_{\rm cl}) + (1-\kappa)\; \mathcal{C}(v_z), \tag{4}$$

where $\kappa(\epsilon)$ is the fraction of stars expelled after the gas is thrown from each cluster. The distribution function of the expanding stars is

$$\mathcal{E}(v_z, M_{\rm cl}) = \mathcal{G}(\sigma_{{\rm exp},z}, \overline{v_z} = 0), \tag{5}$$

since the centre-of-mass of the ensemble is stationary, and where

$$\sigma^2_{{\rm exp},z}(M_{\rm cl}) = \frac{G\, M_{\rm cl}}{\epsilon R_0}\, \zeta + \sigma^2_{0z}, \tag{6}$$

is the velocity variance of the freely expanding populations, with σ_{0z} being the cluster–cluster velocity dispersion resulting from a cluster centre-of-mass velocity distribution that is assumed to be Gaussian (eqn 3). In the present thin MW-disk molecular clouds move relative to each other with a velocity dispersion of about 5 pc/Myr (e.g. Jog & Ostriker 1988), so that $\sigma_{0z} = 5$ pc/Myr is adopted in what follows. Gravitational retardation of the expanding population is approximated through the reduction factor, $\zeta = 1 - \epsilon$, which comes from the loss of kinetic energy, as the fraction, $\kappa\, M_{\rm cl}$, of the cluster expands out of the cluster potential well to infinity ($\sigma^2_{{\rm exp},z} - \sigma^2_{0z} = \sigma^2_{0,\rm cl} - G\, M_{\rm cl}/R_0$, where $\sigma^2_{0,\rm cl}$ is the velocity variance in the cluster prior to gas expulsion, eqn 1).

In what follows it is assumed that the clusters live short lives relative to the age of their galaxy due to evaporation through two-body relaxation; any remaining clusters contributing an insignificant amount of stars. The clusters ultimately leave an extremely long-lived cluster remnant consisting of a strongly hierarchical multiple star system (de la Fuente Marcos 1997; de la Fuente Marcos 1998). The velocity distribution function of stars remaining in the cluster remnants and in the resulting tidal tails and moving groups is summarised as

$$\mathcal{C}(v_z) = \mathcal{G}(\sigma_{{\rm cl},z}, \overline{v_z} = 0). \tag{7}$$

The velocity variance of the stars that ultimately leak out of the bound clusters that form as the nuclei of the expanding associations is approximated here by

$$\sigma^2_{{\rm cl},z} = 2^2\,{\rm pc/Myr} + \sigma^2_{0z}, \tag{8}$$

taking the velocity dispersion in the cluster remnant and of its evaporated stars to be 2 pc/Myr.

Note that $\int_{-\infty}^{+\infty} \mathcal{V}\, dv_z = 1$, and $\kappa = 1 - \epsilon$ with $\epsilon = 0.33$ is adopted based on the results of Kroupa et al. (2001) and discussion therein. The star-formation efficiency, ϵ, may, at most, be a weak function of $M_{\rm cl}$, possibly achieving 0.5 for massive clusters (Tan & McKee 2001; Matzner & McKee 2000).

Each cluster contributes $M_{\rm cl}/m_{\rm av}$ stars to the field population, where $m_{\rm av} = 0.4\, M_\odot$ is assumed to be the invariant average stellar mass (Kroupa 2001b and Reylé & Robin 2001 note possible evidence for a weak dependency on metallicity). The total number of stars that result from a burst of star formation is thus

$$N = \frac{1}{m_{\rm av}} \int\limits_{M_{\rm cl,min}}^{M_{\rm cl,max}} M_{\rm cl}\, \xi(M_{\rm cl})\, dM_{\rm cl} = \frac{\eta'\, M_{\rm disk}}{m_{\rm av}}, \tag{9}$$

where $\xi(M_{\rm cl})\, dM_{\rm cl}$ is the number of clusters with masses in the range $M_{\rm cl}$ and $M_{\rm cl}\, dM_{\rm cl}$, and η' is the fraction of the total galactic disk mass in this population of clusters.

The initial cluster mass function (ICMF), $\xi(M_{\rm cl})$, is extremely hard to infer from the observed distribution of cluster luminosities, because young clusters rapidly evolve dynamically as well as photometrically, and since the light need not follow mass by virtue of mass segregation. Stellar-dynamical evolution of young or forming clusters stands only at the beginning stages (Kroupa 2000; Kroupa et al. 2001), while significant uncertainties in stellar evolution continue to hamper the interpretation of the stellar population in clusters, let alone of integrated cluster luminosities and colours of unresolved clusters (Santos & Frogel 1997). Some progress is evident though, and for example Whitmore et al. (1999), Elmegreen et al. (2000), and Maoz et al. (2001) report, for different star-forming systems, power-law ICMFs,

$$\xi_{\rm P}(M_{\rm cl}) = \xi_{\rm 0P}\, M_{\rm cl}^{-\alpha}, \tag{10}$$

with $\alpha = 1.5 - 2.6$. Old globular clusters, however, are typically distributed normally in $\log_{10} M_{\rm cl} \equiv lM_{\rm cl}$, which is also the distribution of young clusters reported by Fritze–von Alvensleben (2000) for the interacting Antennae galaxies,

$$\xi_{\rm G}(lM_{\rm cl}) = \frac{\xi_{\rm 0G}}{\sqrt{2\,\pi}\; \sigma_{\rm lMcl}} e^{-\frac{1}{2}\left(\frac{lM_{\rm cl} - \overline{lM_{\rm cl}}}{\sigma_{\rm lMcl}}\right)^2}, \tag{11}$$

where $\overline{lM_{\rm cl}} \approx 5.5$ is the mean log-mass and $\sigma_{\rm lMcl} \approx 0.5$ is the standard deviation in log-mass ($M_{\rm cl}$ in units of $M_\odot$), and $\xi_{\rm G}(lM_{\rm cl})\, dlM_{\rm cl}$ is the number of clusters with log-mass in the interval $lM_{\rm cl}$ to $lM_{\rm cl}\, dlM_{\rm cl}$.

From eqn 9,

$$\xi_{\rm 0P} = m_{\rm av}\, N \left(\frac{2 - \alpha}{M_{\rm cl,max}^{2-\alpha} - M_{\rm cl,min}^{2-\alpha}} \right), \qquad \alpha \neq 2, \tag{12}$$

and

$$\xi_{\rm 0G} = m_{\rm av}\, N\;\; 10^{-\overline{lM_{\rm cl}}} e^{-\frac{1}{2}\,(\ln 10\, \sigma_{\rm lMcl})^2} \tag{13}$$

for integration over $lM_{\rm cl}$ with $lM_{\rm cl,min} = -\infty$ to $M_{\rm cl,max} = +\infty$, remembering that $10^x = e^{x\,\ln 10}$.

The distribution function of stellar velocities, $D(v_z)$, that results from the formation of an ensemble of star clusters, becomes

$$D_{\rm P}(v_z; M_{\rm cl,max}, \alpha) = \frac{1}{m_{\rm av}} \int\limits_{M_{\rm cl,min}}^{M_{\rm cl,max}} M_{\rm cl}\;\xi_{\rm P}(M_{\rm cl})\; \mathcal{V}(v_z, M_{\rm cl})\; dM_{\rm cl}, \tag{14}$$

and

$$D_{\rm G}(v_z; \overline{lM_{\rm cl}}, \sigma_{\rm lMcl}) = \frac{1}{m_{\rm av}} \int\limits_{lM_{\rm cl,min}}^{lM_{\rm cl,max}} 10^{lM_{\rm cl}}\ \xi_{\rm G}(lM_{\rm cl})\ \mathcal{V}(v_z, M_{\rm cl})\ dlM_{\rm cl}, \tag{15}$$

with

$$N = \int\limits_{-\infty}^{+\infty} D_{\rm PorG}(v_z)\, dv_z. \tag{16}$$

Equations 14 and 15 are solved by numerically integrating $dD_{\rm P}(v_z)/dM_{\rm cl}$ and $dD_{\rm G}(v_z)/dlM_{\rm cl}$ (initial condition $D_{\rm PorG}(v_z) = 0$ for $M_{\rm cl} = M_{\rm cl,min} = 10\, M_\odot$ or $lM_{\rm cl} = lM_{\rm cl,min} = 1$) using a fifth-order Runge-Kutta method with step-size adaptation (Press et al. 1992) for 1×10^3 velocity bins ranging from $v_{z1} = -500$ pc/Myr to $v_{z2} = +500$ pc/Myr, 500 pc/Myr being taken as the escape velocity from the solar neighbourhood (e.g. BT). The mass interval used for the log-normal ICMF, $lM_{\rm cl,min} = 1$, $lM_{\rm cl,max} = 7$ covers the mass-range of known star clusters, but implies that the distribution $D_{\rm G}$ needs to be scaled numerically to N, since analytical integration cannot determine the correct constant $\xi_{0\rm G}$. Note that the finite escape velocity from the galaxy implies $\int_{v_{z1}}^{v_{z2}} D_{\rm PorG}(v_z)\, dv_z < N$ by a negligible amount for ensembles of clusters ranging up to $M_{\rm cl} \approx 10^7\, M_\odot$. Note also that $lM_{\rm cl,max} = 7$ is consistent with the allowed central number density for the Orion Nebula Cluster (Kroupa 2000).

Results for the power-law ICMF with $\alpha = 1.5$ are plotted in Fig. 1. For Gaussian ICMFs the results are plotted in Fig. 2. In general, the resulting velocity distribution, $D_{\rm PorG}$, is distinctly non-Gaussian. Note the wings of high-velocity stars that become more dominant with increasing $M_{\rm cl,max}$ and $\overline{lM_{\rm cl}}$. The peak at $v_z = 0$ comes from the contribution of $M_{\rm cl} \lesssim 2000\, M_\odot$ clusters, and because $\kappa < 1$ in eqn 4. A cluster–cluster velocity dispersion, $\sigma_{0z} > 5$ pc/Myr, broadens this peak, but here interest is with the extreme case, namely the kinematical implications of cluster-formation in a thin gaseous disk.

2.2. The velocity dispersion and population fraction

Given ${}^0D_{\rm PorG} \equiv D_{\rm PorG}$, the variance of the velocities obtains from

$${}^n\sigma_z^2 = \frac{1}{N} \int\limits_{v_{z1}}^{v_{z2}} v_z^2\ ({}^nD_{\rm PorG}(v_z))\ dv_z, \tag{17}$$

where $n = 0, 1, 2, 3$ are iterations and which, again, is integrated numerically. The entire distribution is used to compute the dispersion ${}^0\sigma_z$. An observer would instead try to isolate distinct sub-populations from the distributions evident in Fig. 1 or 2 given their non-Gaussian form (e.g. Reid, Hawley & Gizis 1995; Gilmore & Wyse 2001). This is modelled here by replacing, in the first iteration, the central, low-velocity peak in ${}^0D_{\rm PorG}$ by a Gaussian with dispersion ${}^0\sigma_z$, i.e. ${}^1D_{\rm PorG} = \mathcal{G}({}^0\sigma_z, \overline{v_z} = 0)$ for those v_z near zero for which ${}^0D_{\rm PorG} \geq \mathcal{G}$, but ${}^1D_{\rm PorG} = {}^0D_{\rm PorG}$ otherwise. This is repeated three times (see Fig. 3), until most of the central maximum is removed, yielding the improved estimate for the velocity dispersion

$$\sigma_z \equiv {}^3\sigma_z. \tag{18}$$

Figs. 4 and 5 show σ_z as a function of ICMF parameters.

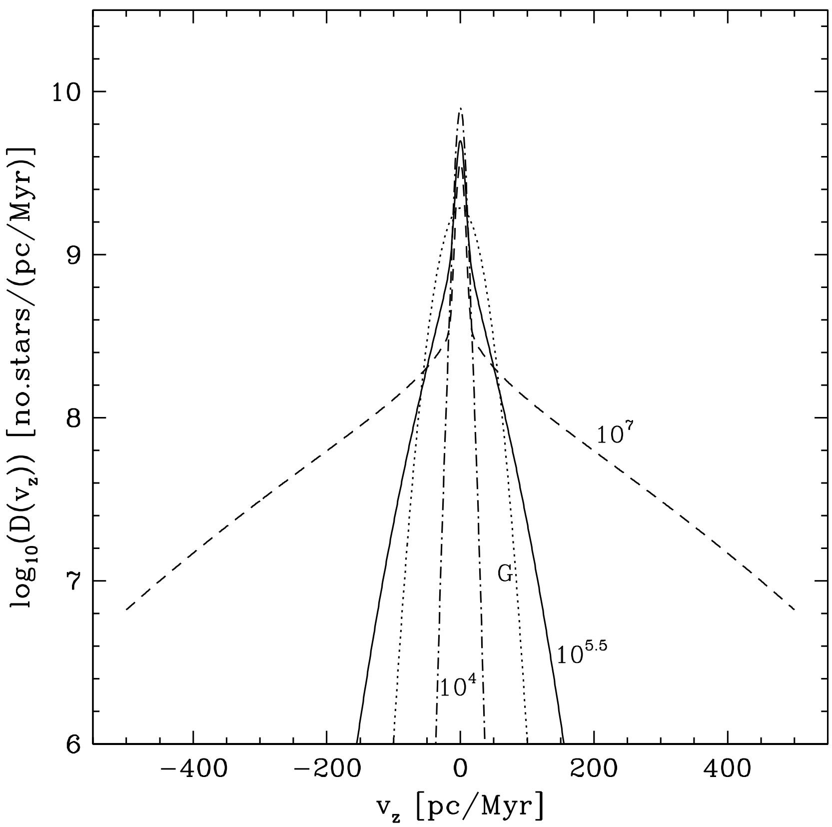

Fig. 1.— Three different velocity distributions, $D_{\rm P}(v_z)$, assuming the ICMF is a power-law with $\alpha = 1.5$ and $M_{\rm cl,min} = 10\,M_\odot$. $M_{\rm cl,max}$ is indicated in $M_\odot$ alongside the curves. For the three models (eqns 17 and 19): ${}^0\sigma_z = 127$ pc/Myr with $\phi = 0.38$ ($M_{\rm cl,max} = 10^7\,M_\odot$), ${}^0\sigma_z = 25.8$ pc/Myr with $\phi = 0.32$ ($M_{\rm cl,max} = 10^{5.5}\,M_\odot$), and ${}^0\sigma_z = 6.9$ pc/Myr with $\phi = 0.04$ ($M_{\rm cl,max} = 10^4\,M_\odot$). The models assume the entire Galactic disk of mass $M_{\rm disk} = 5 \times 10^{10}\,M_\odot$ is buildup of clusters, i.e. $\eta' = 1$, so that each distribution has an area $N = 1.25 \times 10^{11}$ stars (eqn 16). The thin dotted curve is a Gaussian, $\mathcal{G}(\sigma_z = 25.8\,{\rm pc/Myr}, \overline{v_z} = 0)$, with area N.

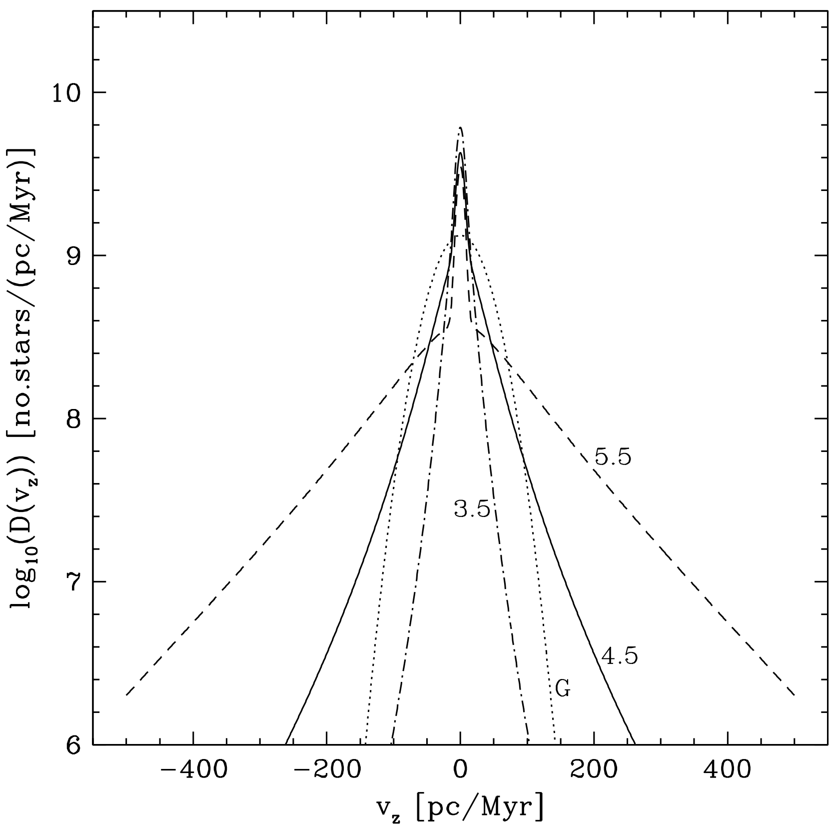

Fig. 2.— As Fig. 1 but assuming the ICMF is a Gaussian in $\log_{10} M_{\rm cl} \equiv lM_{\rm cl}$ with dispersion $\sigma_{\rm lMcl} = 0.5$ and mean $\overline{lM_{\rm cl}}$ shown next to the curves (mass in $M_\odot$). For the four models (eqns 17 and 19): ${}^0\sigma_z = 99.4$ pc/Myr with $\phi = 0.33$ ($\overline{lM_{\rm cl}} = 5.5$), ${}^0\sigma_z = 37.5$ pc/Myr with $\phi = 0.33$ ($\overline{lM_{\rm cl}} = 4.5$), and ${}^0\sigma_z = 12.9$ pc/Myr with $\phi = 0.21$ ($\overline{lM_{\rm cl}} = 3.5$).

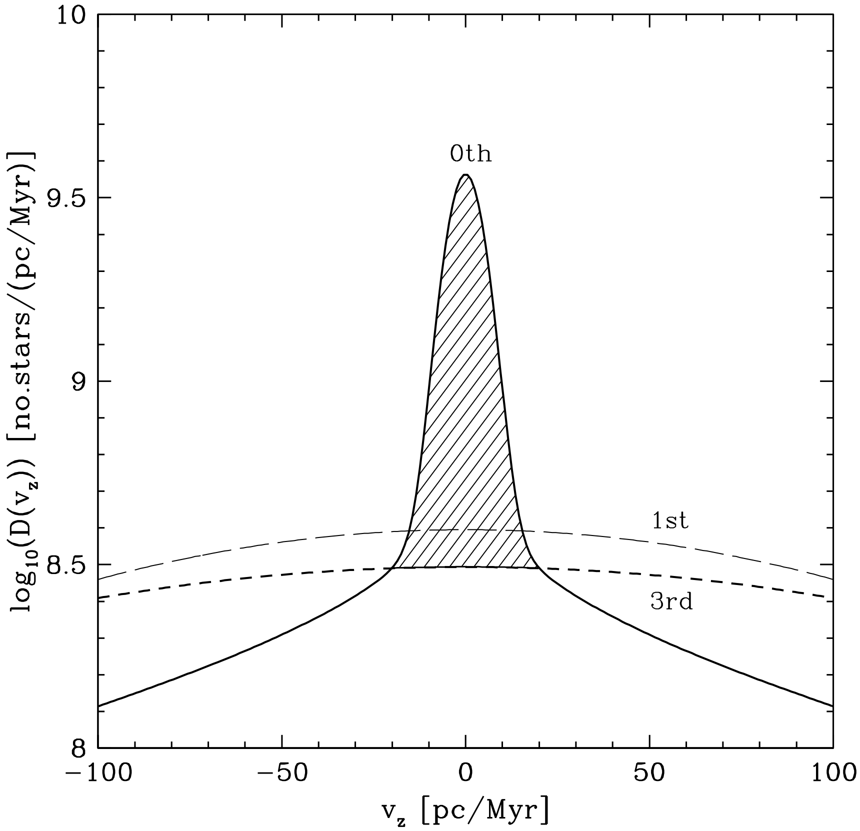

Fig. 3.— Iteration of the velocity distribution function towards an improved estimate of the velocity dispersion characterising the wings in the distribution function. In this example the solid curve is ${}^0D_{\rm PorG} = D_{\rm P}$ with $M_{\rm cl,max} = 10^7\,M_\odot$, $\alpha = 1.5$ and ${}^0\sigma_z = 127$ pc/Myr. The thin long-dashed line is a Gaussian, $\mathcal{G}$, with $\sigma_z = 127$ pc/Myr. Replacing ${}^0D_{\rm P}$ by $\mathcal{G}$ in the central region where $\mathcal{G} < D_{\rm P}$, a first estimate is obtained, ${}^1D_{\rm P}$, which is used to recompute the velocity variance (eqn 17). Two additional such iterations lead to the corrected distribution ${}^3D(v_z)$, shown as the lower solid line, which has the peak (shaded region) removed, and $\sigma_z = 160.1$ pc/Myr (eqn 18). The shaded area contains a fraction $\phi = 0.38$ of all stars in ${}^0D_{\rm P}$.

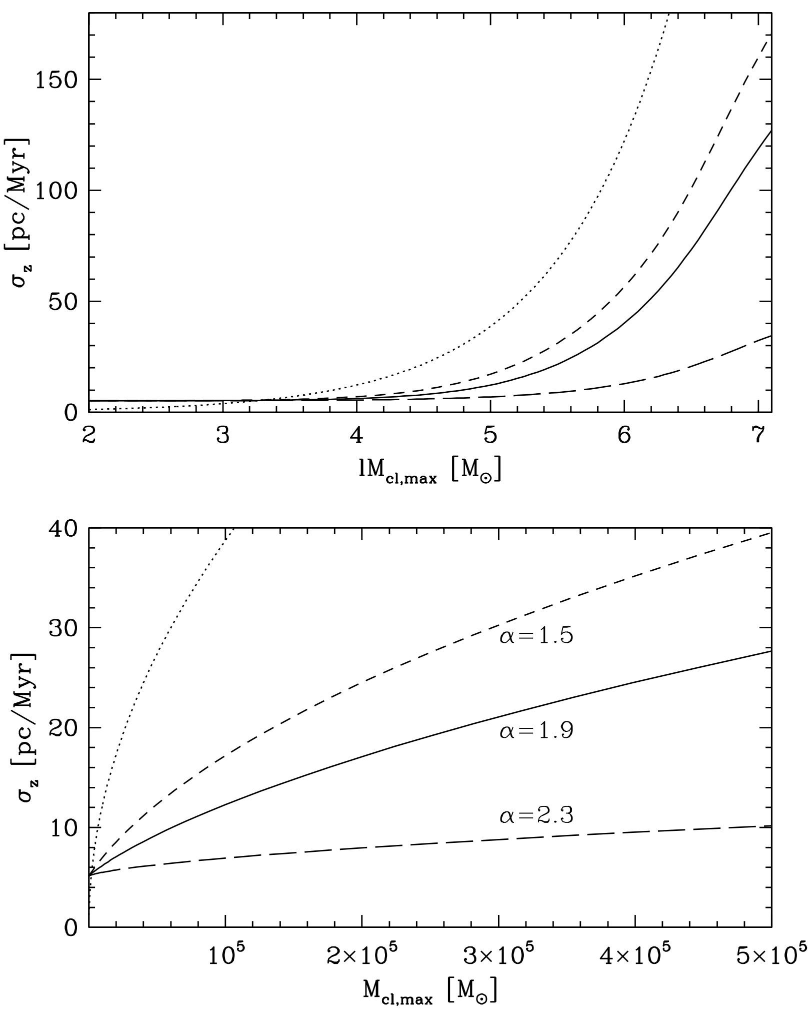

Fig. 4.— Dependence of the velocity dispersion σ_z (eqn 18) on the maximum cluster mass, $M_{\rm cl,max}$, for a power-law ICMF for three different values of the power-law index α (line-types indicated in lower panel; $lM_{\rm cl,max} \equiv \log_{10} M_{\rm cl,max}$). The dotted line is the dependence of $\sigma_{0,\rm cl}$ on $M_{\rm cl}$ ($= M_{\rm cl,max}$ in eqn 1 with $\epsilon R_0 = 0.3$ pc).

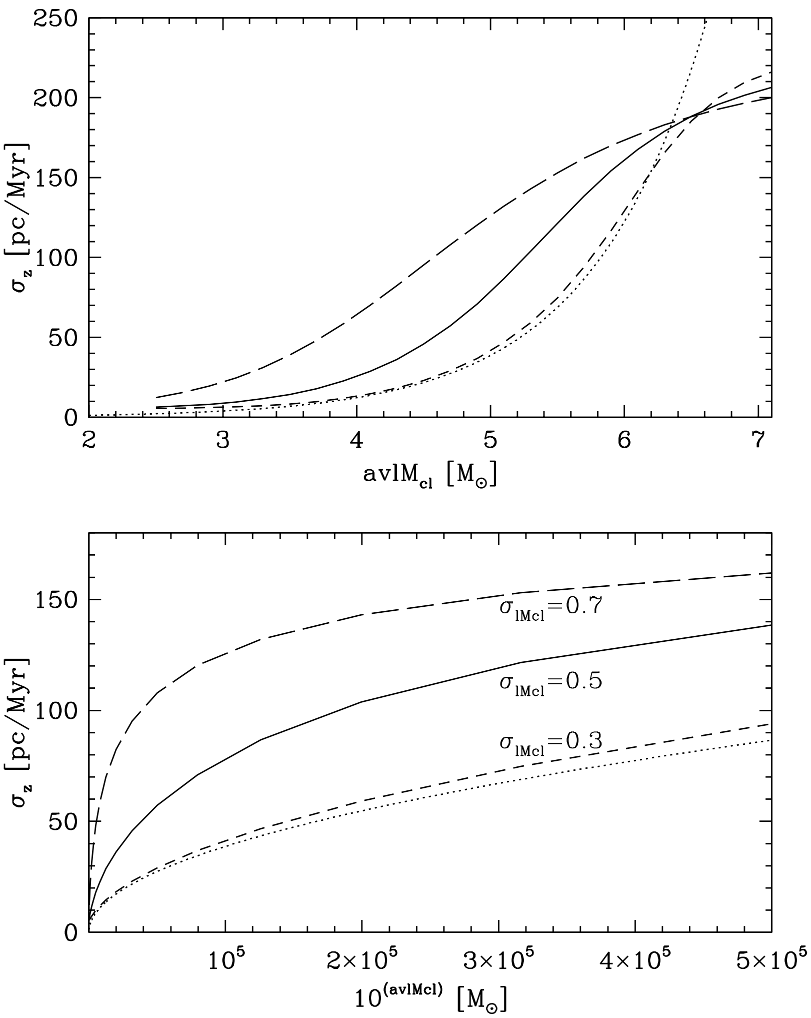

Fig. 5.— Dependence of the velocity dispersion σ_z (eqn 18) on the average log-mass, $avlM_{\rm cl} \equiv \overline{lM_{\rm cl}}$, for three different values of the standard deviation in log-mass, $\sigma_{\rm lMcl}$, for a log-normal ICMF (line-types indicated in lower panel). The dotted line is the dependence of $\sigma_{0,\rm cl}$ on $M_{\rm cl}$ (= $M_{\rm cl,max}$ in eqn 1 with $\epsilon R_0 = 0.3$ pc).

An additional constraint is the relative number of stars in the peak and the whole population,

$$\phi = \frac{{}^0N - {}^3N}{{}^0N}, \tag{19}$$

where ${}^0N \equiv N$ (eqn 16 with $D_{\rm PorG} = {}^0D_{\rm PorG}$), and ${}^nN = \int_{v_{z1}}^{v_{z2}} {}^nD_{\rm PorG}(v_z)\, dv_z$. The fraction of the population in the wings of the velocity distribution is thus $1-\phi$, which is plotted in Fig. 6 for three values of α and $\sigma_{\rm lMcl}$. Admissible models for the thick disk must not have too many stars in the peak, so $1-\phi \gtrsim 0.6$ is imposed, in addition to the constraint on σ_z (Section 3). Note that if the total thick disk amounts to a fraction η' of the mass of the galactic disk, then the observer will identify a fraction $\eta'\,(1-\phi)$ of the galactic disk as being the actual thick disk, whereas $\eta'\,\phi$ is the fraction of the thick disk 'hiding' (subject to adiabatic heating not taken into account here but in Section 2.3) as a thin disk component, but with the same chemical and age distribution as the observationally identified thick disk. Observations suggest

$$\eta = \eta'\,(1-\phi) \approx 0.2 - 0.3 \tag{20}$$

(Section 1) so that $\eta' \lesssim 0.3 - 0.5$. In fact, 'thin-disk' stars with [Fe/H] $\lesssim -0.4$ may simply be the low-velocity ϕ-peak of the thick-disk population.

2.3. Adiabatic heating

If the disk surface mass density, Σ, of a galaxy accumulates over time through infall, the velocity dispersion of already existing stars increases adiabatically leading to an apparent heating of the disk. Jenkins (1992) finds that adiabatic heating helps to explain the empirical Wielen-disk-heating in association with scattering on molecular clouds and spiral arms. The required cloud heating, however, remains incompatible with the observed molecular cloud properties, so that the heating agent is still not fully accounted for.

If the time evolution of the infall rate is $\zeta(t) = d\Sigma/dt$ and outflow can be neglected, then

$$\Sigma(t) = \int_0^{t_0} \zeta(t')\, dt' + \int_{t_0}^{t} \zeta(t')\, dt'; \tag{21}$$

with $\Sigma_{\rm now} \equiv \Sigma(t_{\rm now})$ and $\Sigma_0 \equiv \Sigma(t_0) \equiv \eta'\Sigma_{\rm now}$ (eqns 9 and 20), $t_0 \approx 4$ Gyr being the time when the thick disk material with surface mass density Σ_0 had accumulated (e.g. fig.10.19 in BM; fig. 2 in Fuchs et al. 2001), and $t_{\rm now} \approx 15$ Gyr being the present time. The dependence on Galactocentric distance, $R_{\rm g}$, is dropped for conciseness, since the focus here is on the one sample available, namely near the Sun. Any infall history $\zeta(t)$ can be envisioned. Here only a constant accretion rate onto the thin disk, $\zeta(t) \equiv \zeta = (\Sigma_{\rm now} - \Sigma_0)/(t_{\rm now} - t_0)$, is considered to obtain insights into possible implications.

For highly flattened systems and using Jeans equations in the appropriate limit, $\Sigma = -1/(2\,\pi\, G\rho)\, \partial\rho\, \sigma_z^2/\partial z$ (§4.2 in BT), with the surface density $\Sigma = \int_{-z}^{z} \rho(z')\, dz'$, $\rho(z)$ being the mass density at radial distance R_g from the Galactic centre and height z above the disk plane. Assuming the vertical structure of the MW at any R_g is isothermal ($\sigma_z =$const. with $\rho(z) = \rho_0\, {\rm sech}^2(z/2z_0)$) it follows that $\Sigma = (\sigma_z^2/2z_0\pi G){\rm tanh}(z/2z_0)$. It can thus be assumed that as the mass of the disk builds up, σ_z of existing stars increases following $\sigma_z^2 \propto \Sigma$ (see also §11.3.2 in BM). This implies

$$\sigma_z^2(\Delta t) = \sigma_{z,\rm now}^2 \left(\eta' + (1-\eta')\, \frac{\Delta t}{\Delta t_{\rm now}} \right), \tag{22}$$

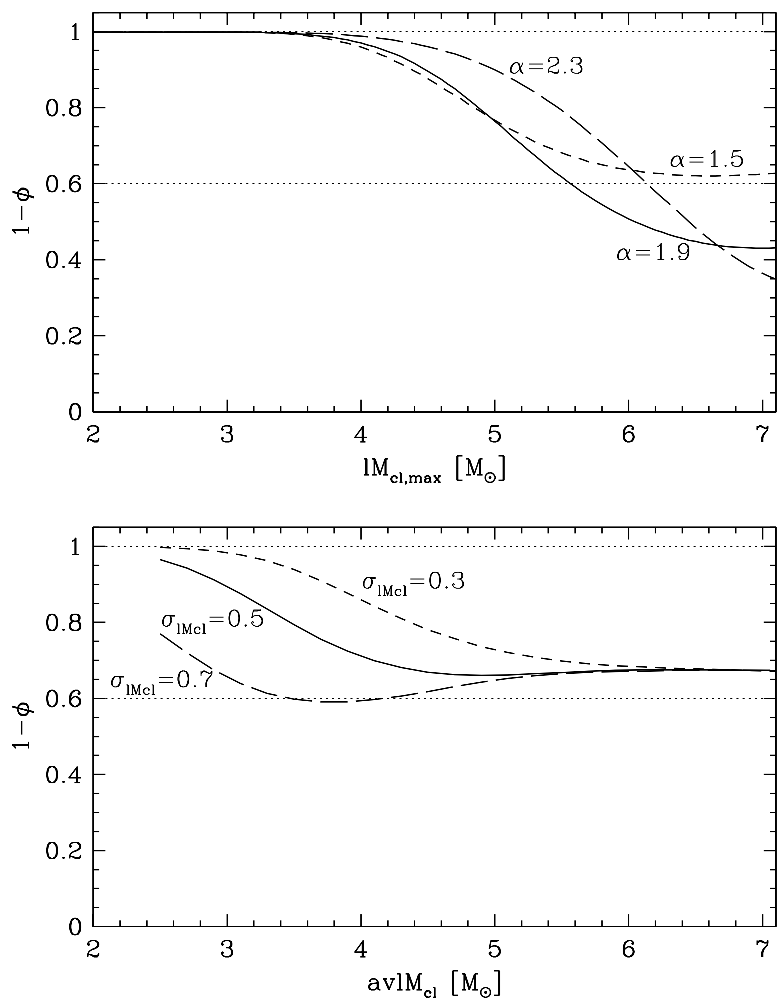

Fig. 6.— Dependence of the fraction of stars in the wing component only, $1-\phi$, (eqn 19) on the maximum cluster mass, $M_{\rm cl,max}$, for a power-law ICMF for three different values of the power-law index α (upper panel, as in Fig. 4), and on the average log-mass, $avlM_{\rm cl} \equiv \overline{lM_{\rm cl}}$, for three different values of the standard deviation in log-mass, $\sigma_{\rm lMcl}$, for a log-normal ICMF (lower panel, as in Fig. 5). The region between the horizontal dotted lines approximately constitutes the range of acceptable thick-disk models ($1-\phi > 0.6$) provided the constraint on $\sigma_{\rm z,obs}$ is fulfilled (Fig. 8 below).

where $\Delta t \equiv t - t_0$ and $\Delta t_{\rm now} \equiv t_{\rm now} - t_0$. The velocity spheroid of existing stars, defined by the velocity dispersions in galactic radial, azimuthal and vertical directions, distorts and rotates as a consequence of differential rotation and disk heating. However, the correction terms to σ_z are negligible for the present treatment (eqn 23 in Jenkins 1992).

Assuming the 'thick disk' accumulated within a few Gyr and formed 30 per cent of the mass now in the MW disk ($\eta' = 0.3$), $\sigma_{0z} \approx 22$ pc/Myr at formation ($\Delta t = 0$) follows from the presently observed value $\sigma_{z,\rm now} \approx 40$ pc/Myr. Similarly, for the old thin disk $\sigma_{\rm z,obs} \approx 25$ pc/Myr (Fuchs et al. 2001), so that $\sigma_{0z} \approx 14$ pc/Myr at star formation from eqn 22, while the observation of young stars suggest $\sigma_{0z} \approx 2 - 5$ pc/Myr (Asiain et al. 1999; Fig. 7).

This thus demonstrates that, if the Galactic disk accumulated mass at a uniform rate over its history, then the required heating of the thin-disk is reduced, as already shown by Jenkins (1992). Nevertheless, as evident in Fig. 7, additional heating is required to increase the velocity dispersion within $\lesssim 3$ Gyr to match the constraints of the Heidelberg group (Jahreiss et al. 1999; Fuchs et al. 2001). Jenkins (1992) shows that molecular clouds and spiral heating cannot account for this 'minimal' heating (minimal because adiabatic heating is taken into account), although the possible short-lived nature of molecular clouds are not taken into account. If these are short lived, with life-times $\approx 10^6 - 10^7$ yr, then an additional heating source may be active through the acceleration of young stars as they transgress time-varying cloud potentials. Asiain et al. (1999) note that different young moving groups appear to experience different heating histories *if* in fact their observed velocity dispersion is assumed to result from the same diffusive mechanism of Wielen (1977). Alternatively, they suggest that the diffusion constants differ between associations ('episodic diffusion').

On the other hand, according to the line-of-argument followed here, individual star-forming events produce associations that expand as a result of gas loss at different rates, and thus with different velocity dispersions depending on the particular star clusters sampled from the ICMF. Expansion thus depends on the intensity of the star-formation episode. The history of $\sigma_{z,\rm obs}(t)$ plotted in Fig. 7 may therefore be a mixture of adiabatic heating, heating from spiral arms and molecular clouds and fluctuations of the velocity dispersion due to clustered star-formation. It will not be easy to disentangle all these effects, given that the history of clustered star formation is not known, but an exemplary attempt is made in Section 4. There the approach is to adopt the age–velocity-dispersion data and Jenkins' model, and to constrain the ICMFs that are required to give the unaccounted-for, or 'abnormal', velocity dispersions.

3. THE POSSIBLE ORIGIN OF THE THICK DISK

Given that clustered star formation is likely to leave a kinematical imprint along the lines of Section 2.1, the following question can now be addressed: Since, so far, no satisfying origin for the thick disk velocity dispersion, $\sigma_{z,\rm obs} \approx 40$ pc/Myr, has been found, may it conceivably be associated with vigorous star-formation during the brief initial assembly of the thin disk? Observations tell us that violent molecular-cloud–dynamics is associated with vigorous star formation, the units of which are star clusters. The maximum cluster mass appears to correlate with the star-formation rate via the pressure in the clouds, which in turn is increased when gas clouds are compressed or collide in perturbed and interacting systems (Elmegreen et al. 2000; Larsen 2001). So maybe the typical $M_{\rm cl}$ was large when the thick disk formed?

Assuming that the velocity dispersion of the thick disk has not changed since its formation, the solution for ICMF parameters can be sought which bring σ_z into agreement with $\sigma_{z,\rm obs}$ at the (arbitrary) 30 per cent level. The solutions are displayed as thin dotted open squares in Fig. 8. The thick open squares in

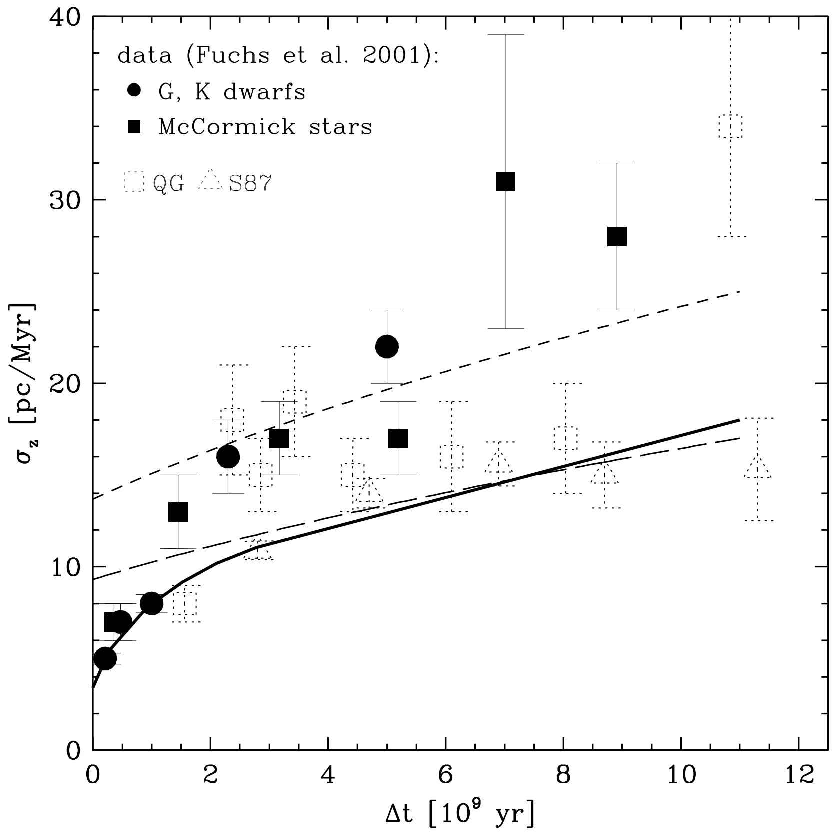

Fig. 7.— The most reliable age–velocity-dispersion data are shown as solid symbols (from fig. 1 in Fuchs et al. 2001). The short-dashed and long-dashed lines are eqn 22 with $\sigma_{z,\rm now} = 25$ and 17 pc/Myr, respectively, assuming that over the past $\Delta t = 11$ Gyr a fraction $1 - \eta' = 0.7$ of the MW disk assembled through infall. The solid curve is Jenkins' (1992) model, scaled to fit the data near $\Delta t = 0$ (his fig. 9), young stars having $\sigma_z \approx 2 - 5$ pc/Myr (Asiain et al. 1999). It takes into account heating through molecular clouds, spiral-wave heating and adiabatic heating through an accreting disk, and thus incorporates all known secular heating mechanisms. The dotted symbols indicate unpublished observational data of Quillen & Garnett (2000, QG), and Stroemgren's (1987, S87) data (see Section 5.2.1 for more details).

Fig. 8 show the solution space for the ICMFs leading to σ_z within 30 per cent of 22 pc/Myr, which is the correct value to fit if the thick disk was adiabatically heated due to a linear growth of the MW disk mass (Section 2.3). The latter solution space is shifted uniformly to smaller cluster masses by about a factor of five to ten. If clusters form with $R_0 = 5$ pc rather than $R_0 = 1$ pc (eqns 2 and 6), then the corresponding solution spaces are shifted to larger masses, as is evident in Fig. 8 as the solid and dotted circles for fitting to the 30 per cent interval around 22 pc/My and 40 pc/Myr, respectively.

4. THE THIN DISK HISTORY

Returning to the discussion at the end of Section 2.3, the solid curve in Fig. 7 shows the most detailed available model, $\sigma_{z,\rm model}(t)$, by Jenkins (1992) for disk heating through spiral arms, molecular clouds and the growth of mass of the MW disk. As stated in the introduction, the model cannot account for $\sigma_{z,\rm obs}(t)$, but it does not take into account possible short life-times of the molecular clouds (Section 2.3).

A bold step is now taken as an example of how the star-formation history of the MW disk may be constrained using the approach discussed here. The residual deviations from the model,

$$\sigma^2_{z,\rm diff}(t) = \sigma^2_{z,\rm obs}(t) - \sigma^2_{z,\rm model}(t) \tag{23}$$

are plotted in the lower panel of Fig. 9. The deviations, eqn 23, show an interesting feature in the age interval 1–4 Gyr and possibly in the age interval 5–7 Gyr. The former possibly correlates with the burst of star formation, deduced by Rocha-Pinto et al. (2000) to be at the 99 per cent level over a constant star-formation rate using chromospheric age estimation, if the data sets have a relative systematic age difference of about 1 Gyr. This is not entirely unrealistic, given that the age estimators are indirect (Fuchs et al. 2001). Hernandez, Valls-Gabaud & Gilmore (2000) also find significant evidence for an increasing star-formation rate with increasing age ($\lesssim 3$ Gyr) using an advanced Bayesian analysis technique to study the distribution of Hipparcos stars in the colour–magnitude diagram. The possible rise in $\sigma_{z,\rm obs}(t)$ near 7 Gyr also finds an increased star formation rate at $t \gtrsim 7$ Gyr when compared to slightly younger ages, but the significance of this feature is not very high.

Assuming, for the purpose of illustration, a power-law ICMF with $\alpha = 1.9$, the upper panel of Fig. 9 plots the maximum cluster mass, $M_{\rm cl,max}$, involved in the star-formation activity and giving rise to

$$\sigma'_{z,\rm diff} = \sqrt{\sigma^2_{z,\rm diff} + \sigma^2_{0z}}, \tag{24}$$

with $\sigma_{0z} = 4$ pc/Myr here; $\sigma'_{z,\rm diff}$ is the correct quantity to fit with $M_{\rm cl,max}$ since eqn 23 only accounts for the increase of the velocity dispersion over the current ($\Delta t \approx 0$) underlying quiescent star-formation activity typified by modest embedded clusters, leading to $\sigma_{0z} \approx 4$ pc/Myr.

The analysis above serves to illustrate that clustered star-formation probably leaves an imprint in the stellar distribution function. Taking Jenkins' (1992) model to be a correct description of the secular increase of σ_z, the above analysis suggests that the star-formation rate in the MW may have been quietening down, that is, that the star-formation rate has been declining, and/or that the ICMF may have been changing towards smaller cluster masses.

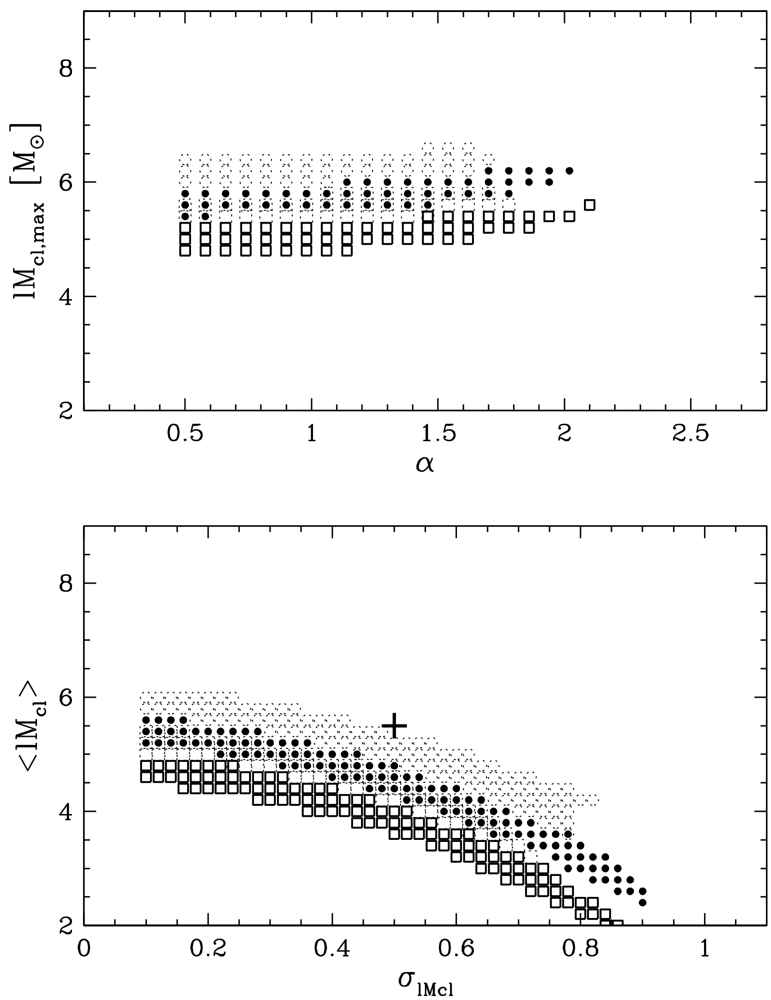

Fig. 8.— **Upper panel:** Solutions in $lM_{\rm cl,max} \equiv \log_{10} M_{\rm cl,max}, \alpha$ space for star-formation occurring in clusters distributed as power-law mass functions. The solution space indicated as thin dotted squares ($R_0 = 1$ pc) and thin dotted circles ($R_0 = 5$ pc) leads to a velocity dispersion, σ_z, within 30 per cent of the observed velocity dispersion of the thick Galactic disk, $\sigma_{z,\rm obs} = 40$ pc/Myr ($0.7\,\sigma_{z,\rm obs} \leq \sigma_z \leq 1.3\,\sigma_{z,\rm obs}$), whereas thick solid squares ($R_0 = 1$ pc) and solid circles ($R_0 = 5$ pc) delineate the solution space leading to an initial thick-disk velocity dispersion lying in the 30 per cent interval around 22 pc/Myr ($15.3 \leq \sigma_z \leq 28.5$ pc/Myr), this being the dispersion corrected for adiabatic heating due to linear growth of the Galactic disk mass after the thick disk formed. All solutions fulfil $1 - \phi > 0.6$. **Lower panel:** As upper panel, but solutions in $\overline{lM_{\rm cl}} \equiv < lM_{\rm cl} >, \sigma_{lM_{\rm cl}}$ space for star-formation occurring in clusters distributed as log-normal mass functions. The thick cross locates the ICMF typically inferred for young cluster populations (Sections 2.1).

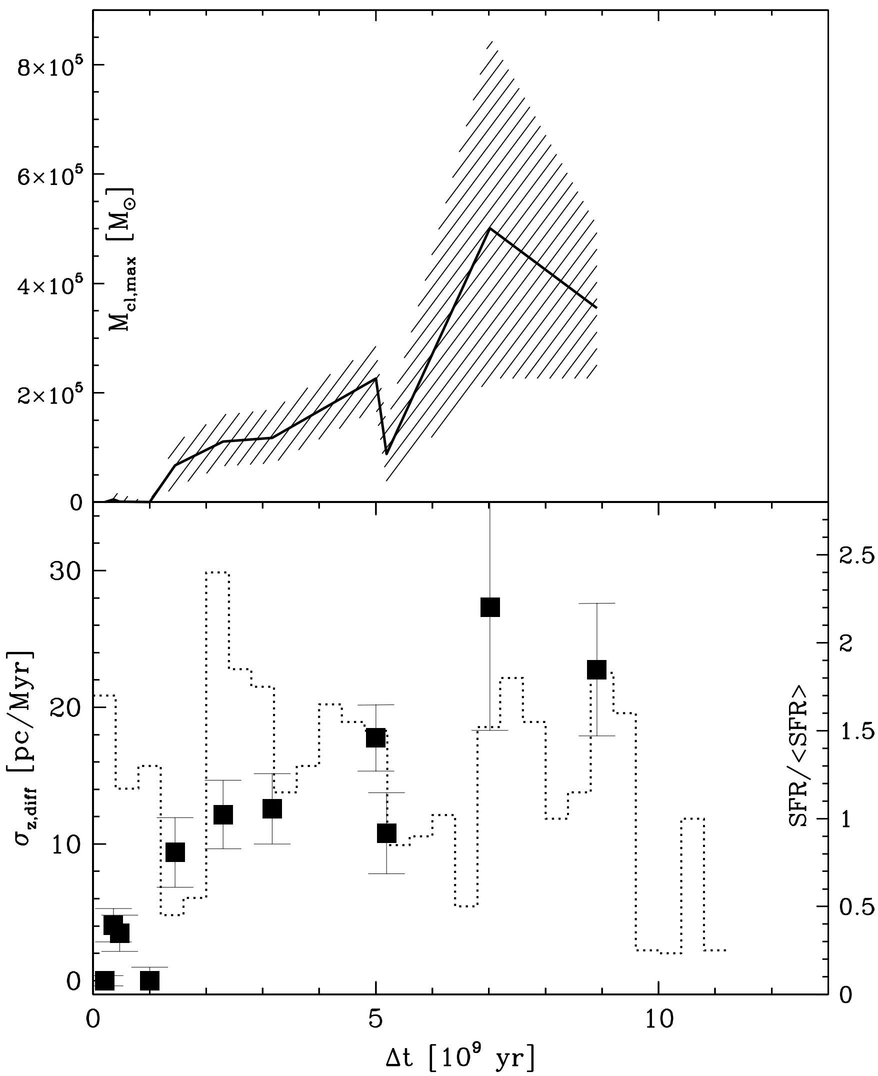

Fig. 9.— **Bottom panel:** The deviations (eqn. 23) of Fuchs et al. (2001) data from Jenkins' (1992) model of the age–velocity-dispersion relation (solid line in Fig. 7) are plotted as solid squares (assuming model has no errors, the error-bars are $\delta\sigma_{z,\rm diff} = (\sigma_{z,\rm Fuchs}/\sigma_{z,\rm diff})\ \delta\sigma_{z,\rm Fuchs}$). The star-formation history of the Galactic disk normalised to the average, SFR/<SFR>, and as estimated by Rocha-Pinto et al. (2000), is shown as a dotted histogram. **Upper panel:** $M_{\rm cl,max}$ leading to $\sigma'_{z,\rm diff}$ (eqn 24) shown in the lower panel, assuming a power-law ICMF with $\alpha = 1.9$.

5. DISCUSSION

The analysis presented in this contribution serves to demonstrate that the kinematics of stars in the MW disk and other galaxies may be influenced by stellar birth in clusters. However, the application to specific kinematical abnormalities in the thin disk, and to the thick disk, is to be viewed as suggestive rather than definitive.

5.1. The model

The model set-up in Section 2.1 is simple but sufficient for this first exploration of how the kinematically hot component emerging from a cluster-forming event may affect the stellar distribution function in a galaxy.

The model (eqn 4) neglects possible variations of the star-formation efficiency with cluster mass and the possible variation of the gas-expulsion time-scale, which may be much longer than the dynamical time of embedded massive clusters (Tan & McKee 2001). If this is so, then the stellar cluster reacts adiabatically to gas removal, and the final velocity dispersion in the cluster will be reduced by a factor ϵ (Mathieu 1983). The velocity distribution function of escaping stars is, in this case, much more difficult to estimate. It nevertheless remains a function of $M_{\rm cl}$, so that the essence of the argument here remains valid, although the detailed solutions evident in Figs. 8 and 9 would change somewhat towards larger cluster masses. Furthermore, the present models do not take into account that the star clusters, which form as nuclei of the expanding stellar associations, continue to add to the thick disk by ejecting high-velocity stars due to three- and four-body encounters. This is evident for massive young clusters (figs. 2 and 3 in Kroupa 2001c) as well as clusters that typically form the Galactic field population (Kroupa 1998). While such events are rare, the implication is that the hot disk component should have a complex metallicity and age structure. A next stage in this project is to assemble synthetic disk populations using high-precision direct N-body calculations of cluster ensembles.

This model predicts a complex velocity field in galaxies that are actively forming star-clusters. In the MW this is evident through expanding OB associations, and the empirical finding that the velocity dispersions of theses differ (Asiain et al. 1999). OB associations are most probably only the central regions of the expansive flow, because massive stars either form centrally concentrated, or they sink to the centres of their embedded cluster essentially on a dynamical timescale. If a young cluster can approximately establish energy equipartition between the stars before gas expulsion, then the massive sub-population will have a significantly smaller velocity dispersion than the low-mass members. Furthermore, an expanding association 'looses' its fast-moving stars early. An observer with a limited survey volume therefore underestimates the velocity dispersion.

The exploratory analysis presented here neglects the other velocity components. Focus is entirely on the component perpendicular to the Galactic disk, easing the analysis. However, according to the notion presented here, the birth of a star cluster leads to an initially isotropically expanding stellar population. The velocity spheroid, given by the ratio of the velocity dispersion perpendicular to the disk ($\sigma_W = \sigma_z$), towards the Galactic centre (σ_U) and in the direction of the motion of the local standard of rest (σ_V), is thus initially spherical. Stars expelled from their cluster towards the Galactic centre accelerate and overtake the other stars, while stars leaving the cluster in the opposite direction are decelerated by the Galactic potential and fall behind. The velocity spheroid is thus distorted due to the differential rotation, and it will be an interesting problem to investigate if the observed velocity spheroid is consistent with the

present notion. For the thin disk Fuchs et al. (2001) gives $\sigma_U : \sigma_V : \sigma_W = 3.5 : 1.5 : 1$, independent of age, while Chiba & Beers (2000) find for the thick disk $\sigma_U : \sigma_V : \sigma_W = 1.31 : 1.43 : 1$. Such differences may partially be due to secular heating mechanisms such as scattering off molecular clouds and spiral arms that decrease σ_W/σ_U (Gerssen, Kuijken & Merrifield 2000). This is more efficient for the colder thin disk population. Adiabatic heating due to the growth of the MW disk also evolves the velocity spheroid, and a passing satellite galaxy induces a radial compression of the gaseous disk which can lead to enhanced star formation and an increased radial velocity dispersion owing to star formation in the radially inflowing gas and the formation of a bar. A full model of the velocity spheroid is thus highly non-trivial and subject to the details of the satellite orbit and the evolution of the Galaxy.

5.2. The thin disk

The literature contains various estimates of age–velocity-dispersion data, and contradictory claims have been made. It is thus useful to cast an independent eye at the situation (Section 5.2.1). The star-formation history of the thin-disk is also briefly discussed in Section 5.2.2.

5.2.1. Data

The most reliable age–velocity-dispersion data come from the (distance-limited) solar-neighbourhood sample contained in the fourth version of the catalogue of nearby stars originally compiled at the Astronomisches Rechen-Institut (ARI) in Heidelberg by the late Gliese and continued by Jahreiss (CNS4, e.g. Jahreiss et al. 1999; Fuchs et al. 2001). This sample has been yielding consistent results over the past 2–3 decades (e.g. Wielen 1977) despite significant improvements such as the inclusion of Hipparcos data for the majority of the stars. The data are shown in Fig. 7.

Since theoretical work has not been able to explain the strong apparent heating of stars with age, the data set has been questioned by a variety of researchers. For example, BM point to the work of Stroemgren (1987). Stroemgren used a preliminary version of the Edvardsson, Andersen & Gustafsson (1993) catalogue to select a sample of stars with $-0.15 \leq$[Fe/H]$\leq +0.15$ and found essentially no increase in σ for ages older than about 4 Gyr, in stark contrast to the results based on the CNS4 data, suggesting that this metal-rich thin-disk subpopulation was not subject to the heating mechanism advocated by Wielen and co-workers at the ARI. From Fig. 7 it in fact follows that the best available theoretical work is in next to excellent agreement with these data. Such a situation may arise if the local stellar sample is contaminated by thick-disk stars, but this would require some thick disk stars to be mis-classified as being significantly younger than the thick-disk bulk. Alternatively, the metal-rich thin-disk population may have been born in modest embedded clusters leading to no kinematical abnormality. Modern data should be used to verify if metal-rich and metal-poor thin-disk populations do indeed follow different age–velocity-dispersion relations.

An additional age–velocity-dispersion data set that is not consistent with the CNS4 data has been submitted for publication by Quillen & Garnett (2000). Again, this data set, which is a re-analysis of the Edvardsson et al. (1993) data, is in perfect agreement with Jenkins' model and with the data of Stroemgren (1987), but also shows the kinematical peculiarity in the age-interval 1–4 Gyr evident in the CNS4 data (Fig. 7).

While the Stroemgren (1987) data are interesting, no follow-up work appeared in a refereed journal.

Also, the Quillen & Garnett (2000) paper will not be published (Quillen, private communication), and Fuchs et al. (2001) demonstrate that their own analysis of the Edvardsson et al. (1993) data yields essentially the same results as they obtain from the CNS4 (fig. 2 in Fuchs et al. 2001). Furthermore, the large velocity dispersions of the older CNS4 thin-disk stars are verified by independent work. Notably, Reid et al. (1995, their table 6) also find $\sigma_z \approx 25$ pc/Myr for stars with $8 < M_V < 15$. Such a large σ_z is also obtained for stars within the very immediate solar-neighbourhood with distances less than 5.2 pc (Kroupa, Tout & Gilmore 1993). Finally, Binney, Dehnen & Bertelli (2000) find, from a statistical analysis of their own new sample of kinematical data essentially the same age–velocity-dispersion relation as advocated by Fuchs et al. (2001, their fig. 4).

The above discussion serves to demonstrate on the one hand that some uncertainties remain in the definition of the age–velocity-dispersion data, but that the evidence lies in favour of the results obtained from the CNS4 (e.g. Fuchs et al. 2001), i.e. that stars have velocity dispersions that increase more steeply with age than theory can account for.

5.2.2. On its history

It is notable that the suggestive finding in Section 4 that the star-formation rate may have declined in the last few Gyr is similar to the conclusion of Fuchs et al. (2001) based on the cumulative star-formation rate as traced by a sample of G and K solar-neighbourhood dwarfs with measured chromospheric emission fluxes (their fig. 5). According to these data, the MW thin disk transformed into a quiescent star-formation mode about 3 Gyr ago. Hernandez et al. (2000) also find a decreasing star-formation rate during the past 3 Gyr (Section 4). Given the good empirical correlation between the mass of the most massive cluster formed and the star-formation rate documented by Larsen (2001) for a sample of 22 galaxies, it would thus not be surprising to find that the star-formation history of the MW disk is reflected in variations of the ICMF, as suggested in the upper panel of Fig. 9.

Janes & Phelps (1994) indeed find an old cluster population of Galactic clusters that have a vertical scale-height of about 300 pc similar to old thin disk stars, and may thus have been heated from $\sigma_{z,0} \approx 5$ pc/Myr to about 15 pc/Myr as described by Jenkins' model (Fig. 7), although cluster-survival of scattering events is controversial, and it may be necessary to allow $\sigma_{0z} > 5$ pc/Myr during the star-burst that formed this cluster population. These clusters are confined to Galactocentric radii $\gtrsim$7.5 kpc being qualitatively consistent with the present MW-disk perturbation hypothesis. Janes & Phelps identify this cluster population with a star-burst about 5–7 Gyr ago, which corresponds to the maximum in the ICMF at about that time as inferred here (Fig. 9).

5.3. The thick disk

The thick-disk ICMF constrained in Section 3 implies that star-clusters may have formed with masses extending to $10^{5-6}\,M_\odot$. Some of these may have survived to the present day. If it is correct that thick-disk star-formation occurred in a thin gaseous disk, as assumed in Section 3 ($\sigma_{0z} = 5$ pc/Myr), then the surviving population of clusters ought to now have a vertical velocity dispersion of about 20 pc/Myr, according to Jenkins' model (Fig. 7).

The extreme assumption $\sigma_{0z} = 5$ pc/Myr was made merely to study if the hot kinematical stellar

component emerging from star-cluster birth can give rise to the thick-disk kinematics for plausible ICMFs. Here the view is that a quiescent thin gas-rich MW disk may have assembled early-on, the MW then essentially being a low-surface brightness disk galaxy. A perturbation by a passing satellite galaxy may have induced significant star formation leading to the thick disk component.

However, it may well be that the thick disk formed with a cluster–cluster velocity dispersion $\sigma_{0z} \approx 22$ pc/Myr due to the probably turbulent and chaotic conditions leading to the assembly of the thin disk, later being heated adiabatically to 35 pc/Myr. In this alternative and maybe more plausible scenario, the resulting ICMF solutions would be only slightly shifted to lower cluster masses (Fig. 8). Fossils of this vigorous star-formation event with $\sigma_{0z} \approx 22$ pc/Myr may be the metal-rich MW globular cluster system which has a density distribution very similar to the stellar thick disk (e.g. BM).

According to Minniti (1996) and Forbes, Brodie & Larsen (2001) a large fraction of these metal-rich globular clusters may rather belong to a bulge population, so that a definitive identification of metal-rich globular clusters as being the fossils of the thick-disk star-formation events cannot be made. Any such population of clusters is likely to have suffered some orbital decay towards the MW disk through non-isotropic dynamical friction on the disk (Binney 1977), implying that the original thickness of the metal-rich globular cluster disk population may have been larger than the present value, possibly compromising its association with the stellar thick disk.

6. CONCLUSIONS

The age–velocity-dispersion relation for the MW is addressed by considering the effects that star-cluster formation may have on the velocity field of stars.

Star clusters form with star-formation efficiencies $\epsilon < 0.4$ and they are probably near global gravitational equilibrium just before the remaining gas is expelled. Observational evidence suggests that gas expulsion is rapid, so that the majority of stars expand outwards with a velocity dispersion that is related to the velocity dispersion prior to gas expulsion.

This scenario implies that the distribution function of stars in galaxies should reflect these events. Peculiar kinematical features, such as enhanced velocity dispersions for stars of particular ages, may thus be the result of specific star-formation events, or bursts, that produced star-clusters with masses larger than that typical under more quiescent star-forming conditions. An empirical correlation between cluster mass and star-formation rate is established by Larsen (2001).

The calculations presented here show that the velocity distribution function of stars emerging from a star-formation event is distinctly non-Gaussian with a low-dispersion ϕ-peak and broad wings (Figs. 1 and 2). It is noteworthy that Reid et al. (1995) find that the velocity distribution of solar-neighbourhood stars shows structure reminiscent of the present models. Ancient thin-disk stars with overlapping metallicities to those of thick-disk stars may, according to this interpretation, be the kinematically cold ϕ-peak of the star-formation burst that formed the thick disk.

Examples of star-formation bursts leading to abnormal kinematical signatures may be the Galactic thick disk, and possible star-formation bursts about 1–4 Gyr and 5–7 Gyr ago evident in the age–velocity--dispersion data for the solar neighbourhood. These kinematical 'abnormalities' are analysed here by calculating the velocity distribution function assuming stars form in ensembles of star clusters distributed either as power-law or as log-normal initial cluster mass functions (ICMFs). The allowed ICMFs are

constrained (Figs. 8 and 9). The results are plausible when compared to direct surveys of the ICMF (Section 2.1). The putative star-formation burst 5–7 Gyr ago may be associated with the population of old (and thus initially relatively massive) Galactic clusters identified by Janes & Phelps (1994).

Satellite infall or perturbation may still be responsible for a burst of star formation that allows more massive clusters to form, but, as shown here, heating of galactic disks may not require direct satellite infall into the disk. It is thus interesting that Rocha-Pinto et al. (2000) find possible correlations between their star-formation history and the orbit of the Magellanic Clouds, which in turn can be correlated with the above mentioned age–velocity-dispersion abnormalities (Fig. 9). Schwarzkopf & Dettmar (2000; 2001) find that perturbed disk galaxies are significantly thicker than isolated disk galaxies. The present notion does not exclude that disk thickening can also be induced through satellites or high-velocity clouds hitting disks directly.

The notion raised here readily carries over to populating the Galactic spheroid through forming star clusters, only the most massive of which survived to become the present-day globulars. It also carries over to properties of the distribution function of moving groups associated with the formation of individual distant globular clusters in the out-reaches of the Galactic halo.

The concept introduced here relies on the unbound star-cluster population expanding with a velocity that depends on the cluster configuration before gas expulsion (eqn. 4). This can be tested with high-precision astrometry. A perfect test-bed is the Large Magellanic Cloud which is forming star clusters profusely, probably as a result of being tidally perturbed (van der Marel 2001). Thus, upcoming space-astrometry missions (DIVA: Röser 1999; GAIA: Lindegren & Perryman 1996 and Gilmore et al. 1998) should measure complex velocity fields in the LMC, since each very young but gas-free cluster should have associated with it an approximately radially expanding population of stars with an overall velocity dispersion characteristic of the conditions before gas-expulsion. Evidence for this is emerging (Section 2). If an empirical upper limit on the velocity dispersion of expanding associations independent of $M_{\rm cl}$ for some value larger than $M_{\rm cl,crit}$ can be found, then this would serve as an important constraint on the star-formation efficiency and gas-expulsion time for clusters more massive than $M_{\rm cl,crit}$. It will also be necessary to quantify the evolution of the velocity spheroid ($\sigma_U : \sigma_V : \sigma_W$) as an improved test of the model against available observational constraints.

Acknowledgements

I thank Christian Theis for friendly discussions.

REFERENCES

Asiain R., Figueras F., Torra J., 1999, A&A, 350, 434

Binney J., 1977, MNRAS, 181, 735

Binney J., Merrifield M., 1998, Galactic Astronomy, Princeton University Press (BM)

Binney J., Tremaine S., 1987, Galactic Dynamics, Princeton University Press (BT)

Binney J., Dehnen W., Bertelli G., 2000, MNRAS, 318, 658

Boily C.M., Kroupa P., 2001, in Modes of Star Formation and the Origin of Field Populations, E.K. Grebel, W. Brandner (eds), ASP Conf. Ser, in press (astro-ph/0102024)

Bosch G., Selman F., Melnick J., Terlevich R., 2001, A&A, in press (astro-ph/0110345)

Brown A.G.A., 2001, in Modes of Star Formation and the Origin of Field Populations, eds. E.K. Grebel, W. Brandner, ASP Conf. Series, in press (astro-ph/0101207)

Burkert A., Truran J.W., Hensler G., 1992, ApJ, 391, 651

Buser R., Rong J., Karaali S., 1999, A&A, 348, 98

Chereul E., Crézé M., Bienaymé O., 1998, A&A, 340, 384

Chiba M., Beers T.C., 2000, ApJ, 119, 2843

Dehnen W., Binney J., 1998, MNRAS, 294, 429

de la Fuente Marcos R., 1997, A&A, 322, 764

de la Fuente Marcos, R., 1998, A&A, 333, L27

Elmegreen B.G., Efremov Yu., Pudritz R.E., Zinnecker H., 2000, in Protostars and Planets IV, V. Mannings, A.P. Boss, S.S. Russell (eds), Univ. of Arizona Press, p. 179

Forbes D.A., Brodie J.P., Larsen S.S., 2001, ApJ, 556, L83

Fritze–von Alvensleben U., 2000, in Massive Stellar Clusters, A. Lancon, C.M. Boily (eds), ASP Conf. Series, Vol. 211, p.3

Fuchs B., Dettbarn C., Jahreiss H., Wielen R., 2001, in STAR2000: Dynamics of Star Clusters and the Milky Way, eds S. Deiters, B. Fuchs et al., ASP Conf. Series, in press (astro-ph/0009059)

Gerssen J., Kuijken K., Merrifield M.R., 2000, MNRAS, 317, 545

Gilmore G., Perryman M., Lindegren L., et al., 1998, in Astronomical Interferometry, ed. R.D. Reasenberg, Proc. SPIE Vol. 3350, p. 541

Gilmore G., Wyse R.F.G., Kuijken K., 1989, ARAA, 27, 555

Gilmore G., Wyse R.F.G., 2001, in STAR2000: Dynamics of Star Clusters and the Milky Way, eds S. Deiters, B. Fuchs et al., ASP Conf. Series, in press (astro-ph/0104242)

Hillenbrand L.A., Hartmann L.W., 1998, ApJ, 492, 540

Ho L.C., Filippenko A.V., 1996, ApJ, 472, 600

Huang S., Carlberg R.G., 1997, ApJ, 480, 503

Jahreiss H., Fuchs B., Wielen R., 1999, ApSS, 265, 247

Janes K.A., Phelps R.L., 1994, AJ, 108, 1773

Jenkins A., 1992, MNRAS, 257, 620

Jog C.J., Ostriker J.P., 1988, ApJ, 328, 404

Jones B.F., Walker M.F., 1988, AJ, 95, 1755

Kaas A.A., Bontemps S., 2001, in From Darkness to Light: Origin and Evolution of Young Stellar Clusters, Th. Montmerle, Ph. André (eds), ASP Conf. Series, in press (astro-ph/0008460)

Kerber L.O., Javiel S.C., Santiago B.X., 2001, A&A, 365, 424

Kroupa P., 1995, MNRAS, 277, 1491

Kroupa P., 1998, MNRAS, 298, 231

Kroupa P., 2000, NewA, 4, 615

Kroupa P., 2001a, in From Darkness to Light: Origin and Evolution of Young Stellar Clusters, Th. Montmerle, Ph. André (eds), ASP Conf. Series, in press (astro-ph/0010405)

Kroupa P., 2001b, MNRAS, 322, 231

Kroupa P., 2001c, in The Formation of Binary Stars, IAU Symp. 200, eds. H. Zinnecker, R. Mathieu, ASP Conf. Series, in press (astro-ph/0010347)

Kroupa P., Petr M.G., McCaughrean M.J., 1999, NewA, 4, 495

Kroupa P., Aarseth S.J., Hurley J.R., 2001, MNRAS, 321, 699

Kroupa P., Tout C.A., Gilmore G., 1993, MNRAS, 262, 545

Lada C.J., Lada E.A., 1991, in K. James (ed.), The Formation and Evolution of Star Clusters, ASP Conf. Series 13, 3

Lancon A., Boily C.M. (eds), 2000, Massive Stellar Clusters, ASP Conf. Series, Vol. 211, San Francisco

Larsen S.S., 2001, in Extragalactic Star Clusters, eds E.K. Grebel, D. Geisler, D. Minniti, IAU Symp., in press (astro-ph/0105489)

Larsen S.S., Brodie J.P., Huchra J.P., et al., 2001, AJ, 121, 2974

Lindegren L., Perryman M.A.C., 1996, A&AS, 116, 579

Maoz D., Barth A.J., Ho L.C., Sternberg A., Filippenko A.V., 2001, AJ, in press (astro-ph/0103213)

Massey P., Hunter D.A., 1998, ApJ, 493, 180

Mathieu R.D., 1983, ApJ, 267, L97

Matzner C.D., McKee C.F., 2000, ApJ, in press (astro-ph/0007383)

Minniti D., 1996, ApJ, 459, 175

Norris J.E., 1999, ApSS, 265, 213

Press W.H., Teukolsky S.A., Vetterling W.T., Flannery B.P., 1994, Numerical Recipes, Cambridge University Press (2nd edition)

Quillen A.C., Garnett D.R., 2000, ApJ, submitted (astro-ph/0004210)

Reid I.N., Hawley S.L., Gizis J.E., 1995, AJ, 110, 1838

Reylé C., Robin A.C., 2001, A&A, in press (astro-ph/0105199)

Robin A.C., Haywood M., Crźé M., Ojha D.K., Bienaymé O., 1996, A&A, 305, 125

Rocha-Pinto H.J., Scalo J., Maciel W.J., Flynn C., 2000, A&A, 358, 869

Röser S., 1999, Reviews in Modern Astronomy, 12, 97

Santos J.F.C., Frogel J.A., 1997, ApJ, 479, 764

Schwarzkopf U., Dettmar R.-J., 2000, A&A, 361, 451

Schwarzkopf U., Dettmar R.-J., 2001, A&A, 373, 402

Seleznev A.F., 1997, Astronomy Reports, 41, 746

Sellwood J.A., Nelson R.W., Tremaine S., 1998, ApJ, 506, 590

Sirianni M., Nota A., Leitherer C., et al., 2000, ApJ, 533, 203

Smith L.J., Gallagher III, J.S., 2001, MNRAS, in press (astro-ph/0104429)

Stroemgren B., 1987, in The Galaxy, eds. G. Gilmore, B. Carswell, NATO ASI Series, R.Reidel Publ., p.229

Tan J.C., McKee C.F., 2001, in Starbursts: Near and Far, Ringberg Castle, Germany, 10-15 September 2000 (astro-ph/0012005)

Vallenari A., Bertelli G., Schmidtobreick L., 2000, A&A, 361, 73

van der Marel R.P., 2001, AJ, in press (astro-ph/0105340)

Velazquez H., White S.D.M., 1999, MNRAS, 304, 254

Wielen R., 1977, A&A, 60, 263

Williams B.F., Hodge P.W., 2001, ApJ, in press (astro-ph/0105506)

Whitmore B.C., 2001, in STScI Symposium Series 14, ed. M. Livio, in press (astro-ph/0012546)

Whitmore B.C., Zhang Q., Leitherer C., Fall S.M., Schweizer F., Miller B.W., 1999, AJ, 118, 1551